RIM: Robust Intersection Management for Connected Autonomous Vehicles

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Why Automated intersections?

- Accidents at intersection
  - Around **30% of fatal crashes** have happened in intersection areas, most of which, involved **human errors.** [FHA]
- Traffic Congestion
  - On the average, each person in the US spends around **42 hours per year** stuck in the traffic [FHA]
- As cars become autonomous, so too can intersections
  - Intersection Management using V2I

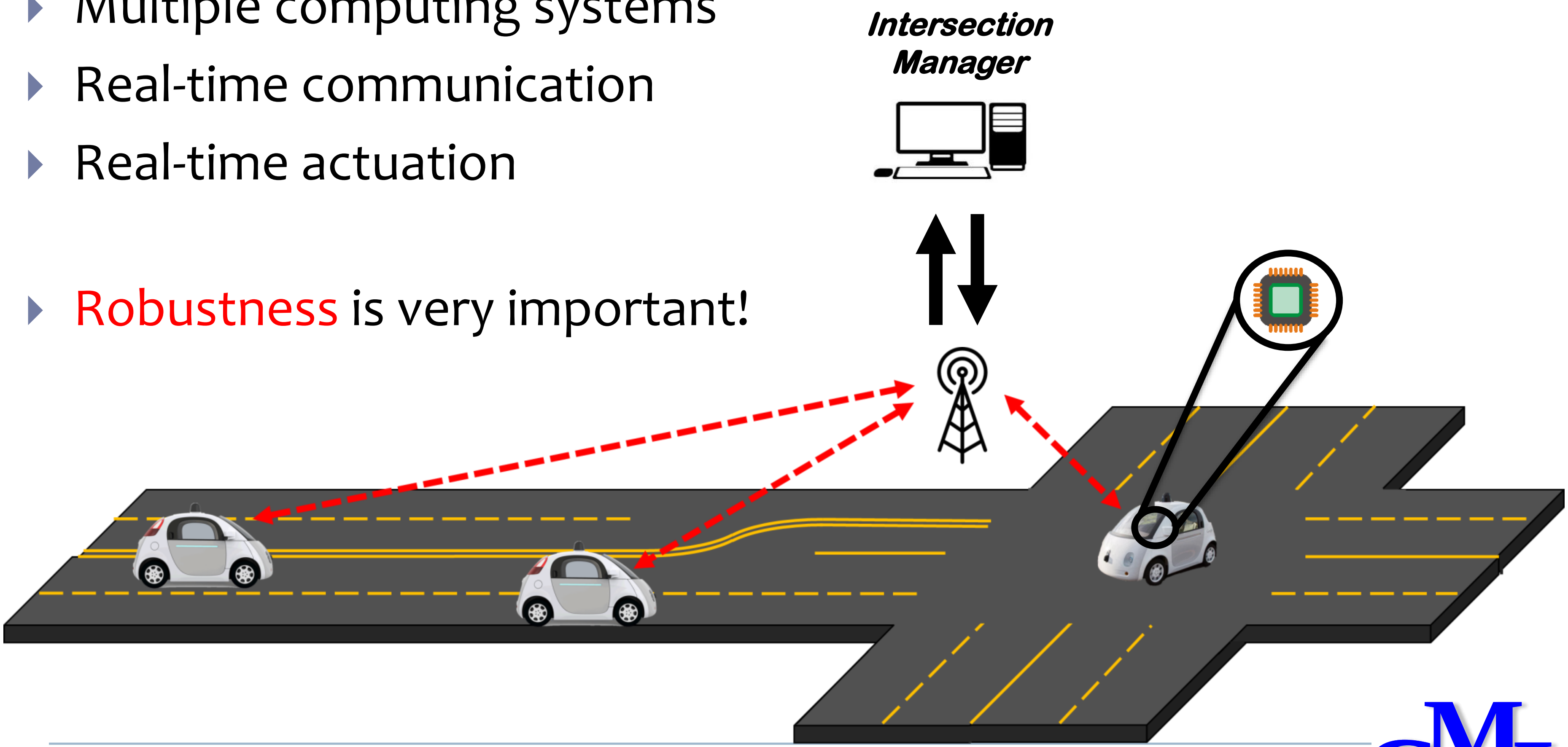
[FHA] Roadway Safety Data Dashboards, US Department of Transportation - Federal Highway Administration

Intersection Manager (IM)

- An Infrastructure communicating with incoming vehicles.

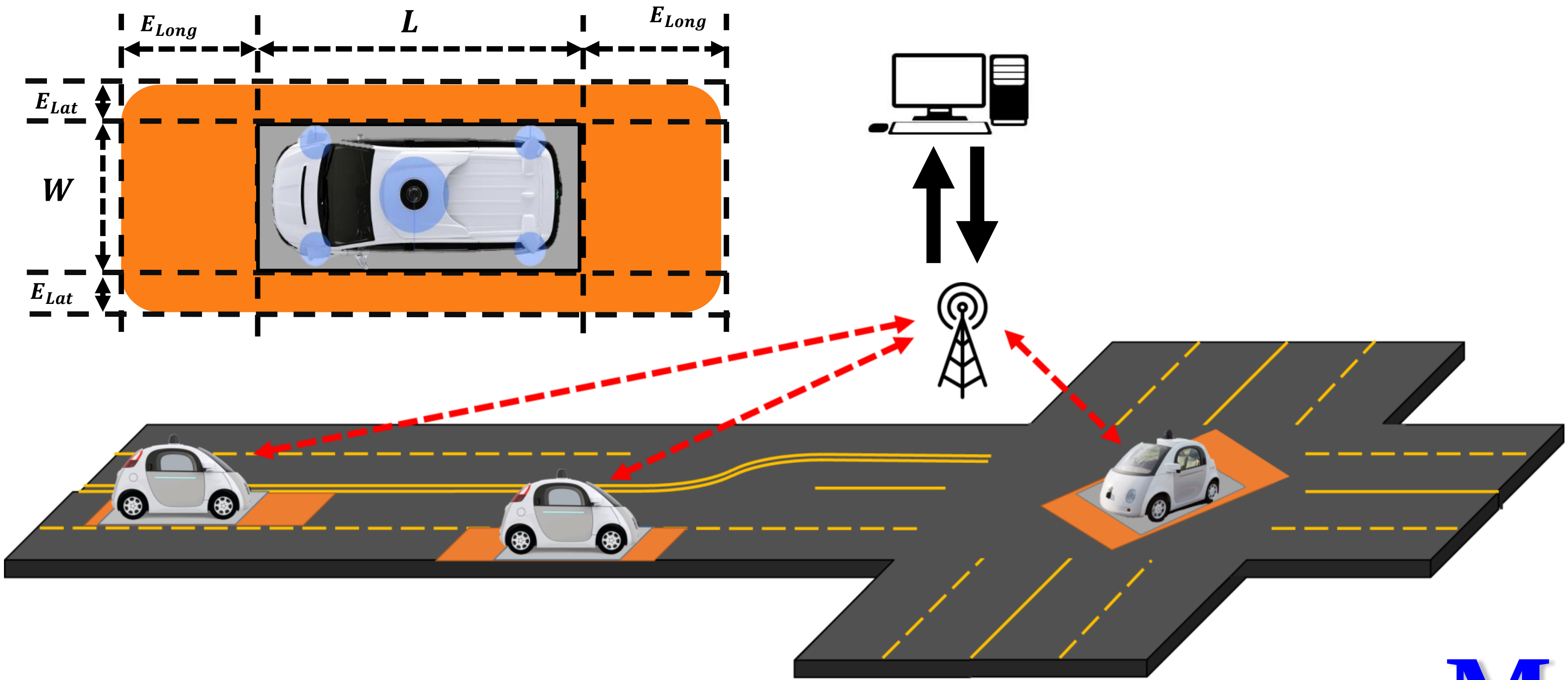
- Multiple computing systems
- Real-time communication
- Real-time actuation

- Robustness is very important!



Safety buffer

- Localization of autonomous vehicle is challenging!
- IM should consider a safety buffer around each vehicle to account for uncertainties in vehicles position.



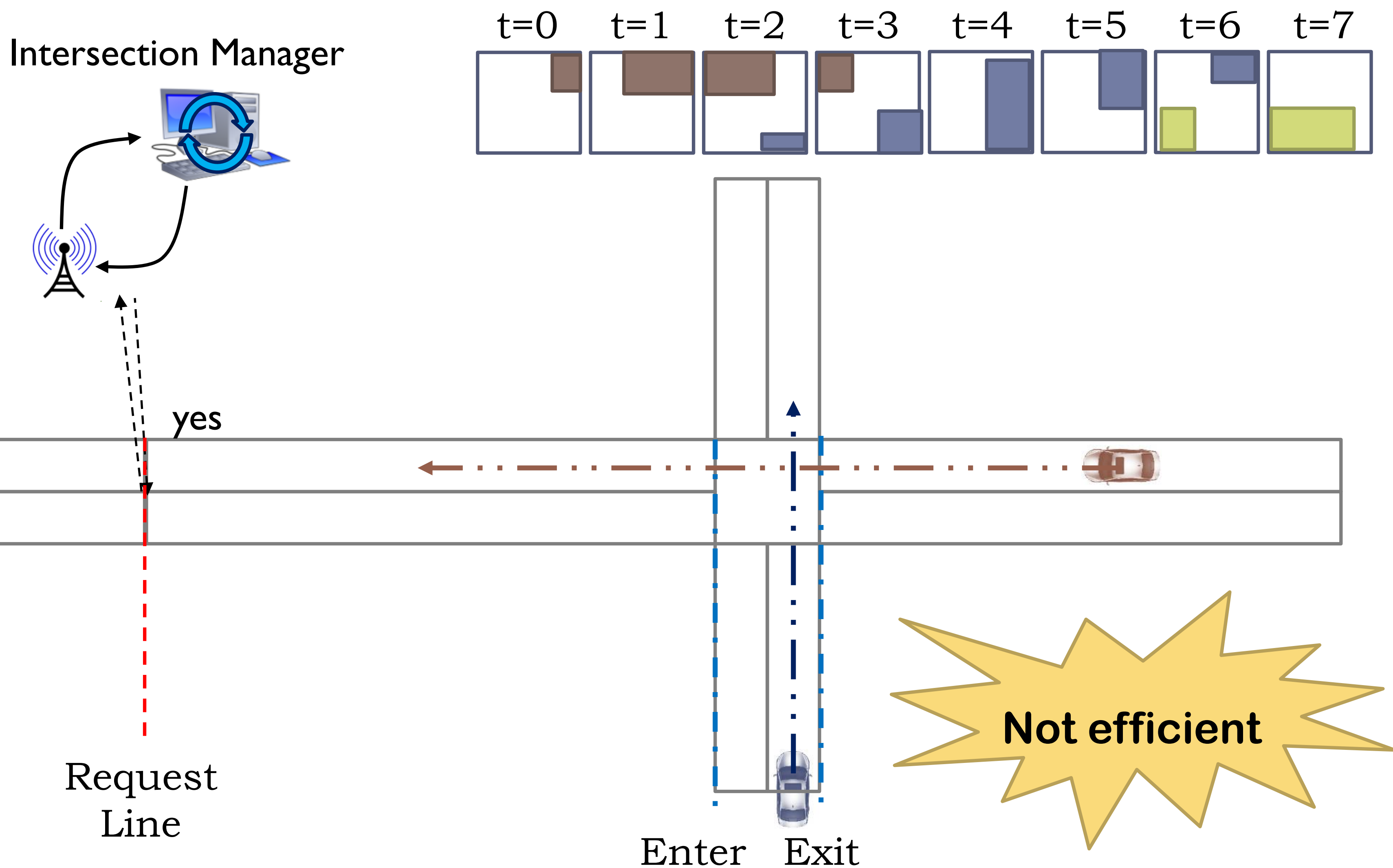
Existing Approaches

- Query-based Intersection Management (QB-IM)
  - Vehicles send estimated time of arrival and velocity of arrival to IM
  - IM accepts/rejects the request
  - AIM (Autonomous Intersection Management) [1]
- Velocity Assignment Intersection Management (VA-IM)
  - Vehicles send their position and velocity
  - A target velocity is assigned to the vehicle
  - Cooperative Vehicle Intersection Control (CVIC) [2]

[1] Dresner, Kurt, and Peter Stone. "A multiagent approach to autonomous intersection management." *Journal of artificial intelligence research* 31 (2008): 591-656.

[2] Lee, Joyoung, and Byungkyu Park. "Development and evaluation of a cooperative vehicle intersection control algorithm under the connected vehicles environment." *IEEE Transactions on Intelligent Transportation Systems* 13.1 (2012): 81-90.

QB-IM *(Query-based Intersection Management)*



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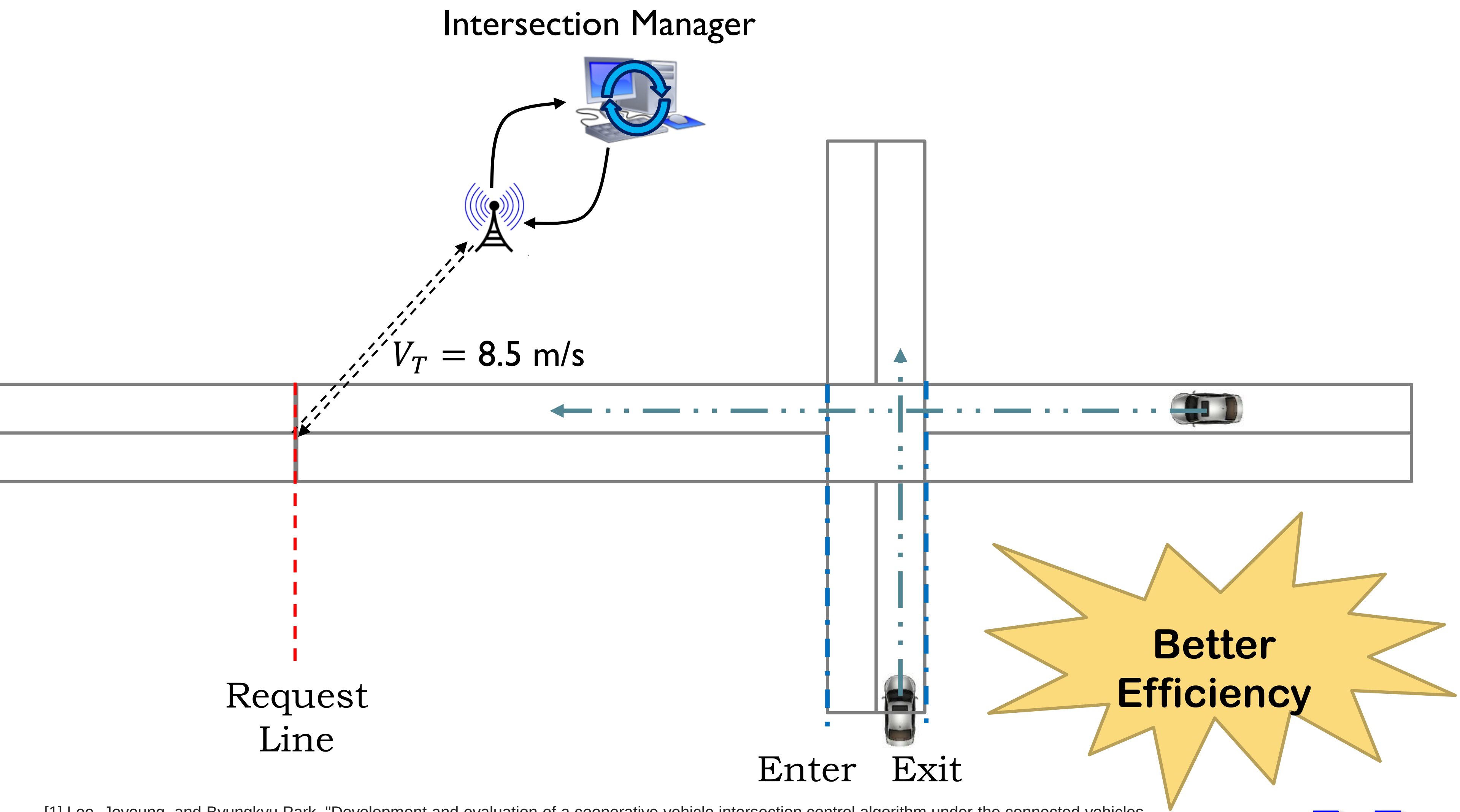
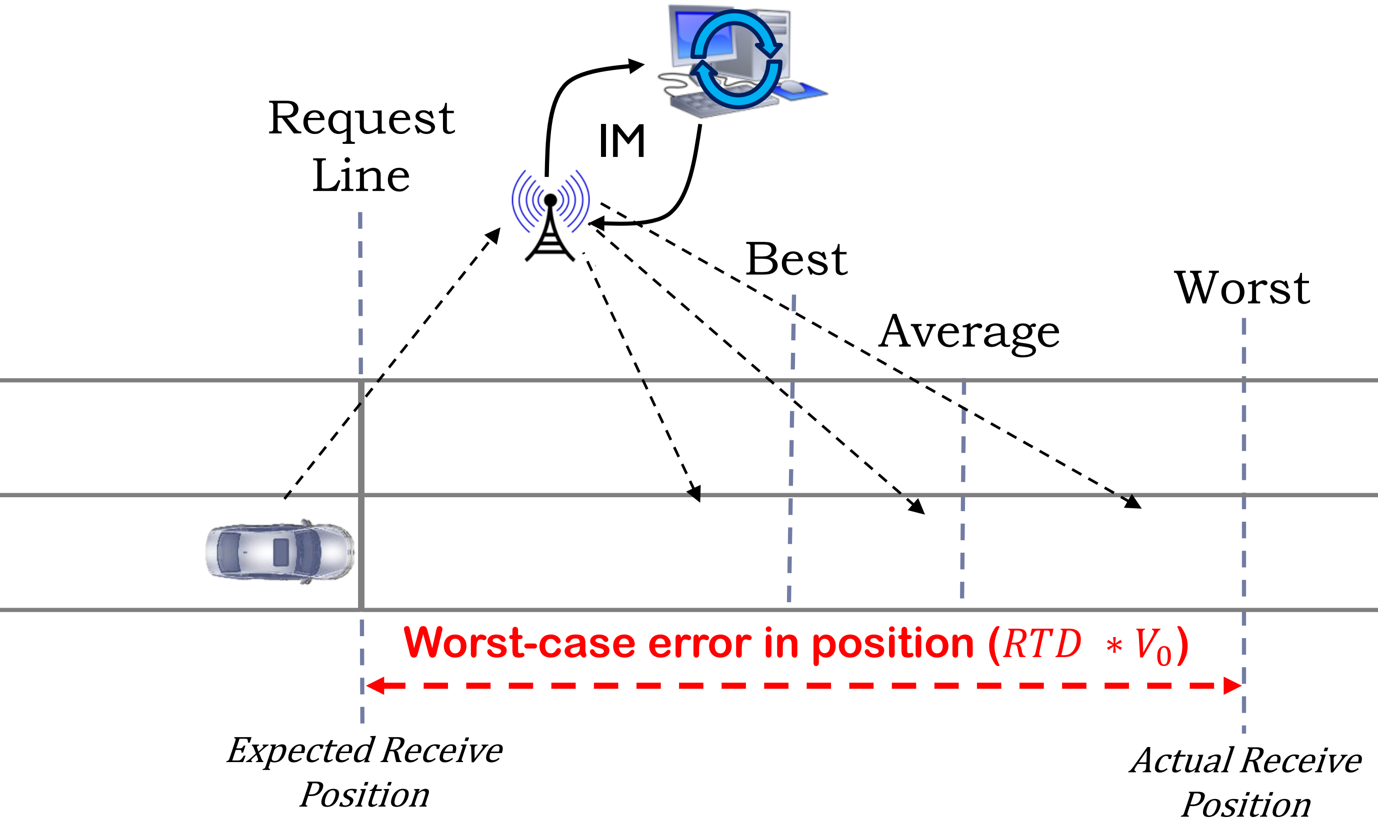
VA-IM *(Velocity Assignment Intersection Management)*



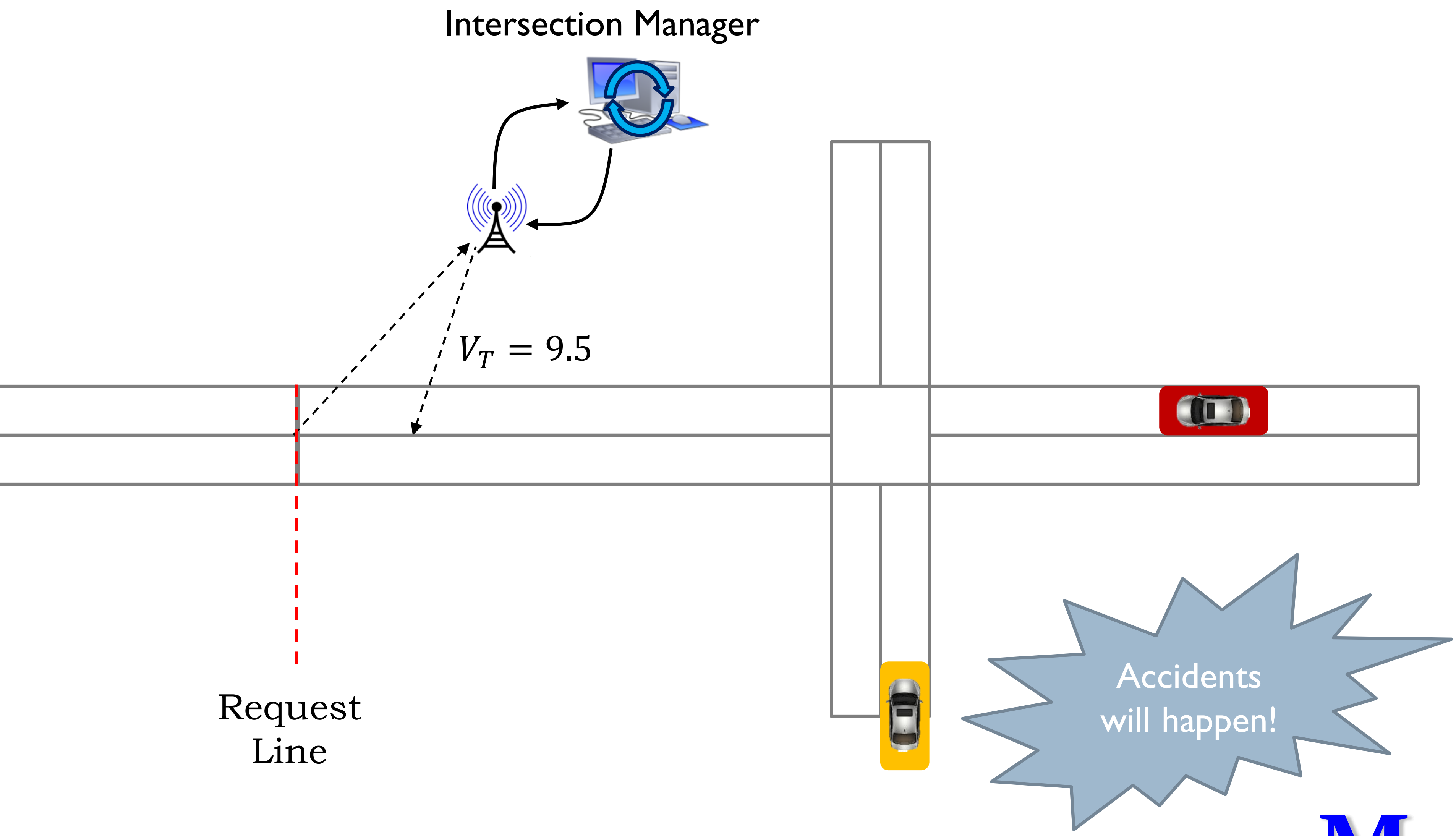
[1] Lee, Joyoung, and Byungkyu Park. "Development and evaluation of a cooperative vehicle intersection control algorithm under the connected vehicles environment." *IEEE Transactions on Intelligent Transportation Systems* 13.1 (2012): 81-90.

Timing Problem in VA-IM

- Round Trip Delay (RTD) is ignored.
  - Inconsistency between vehicle position and what IM thinks



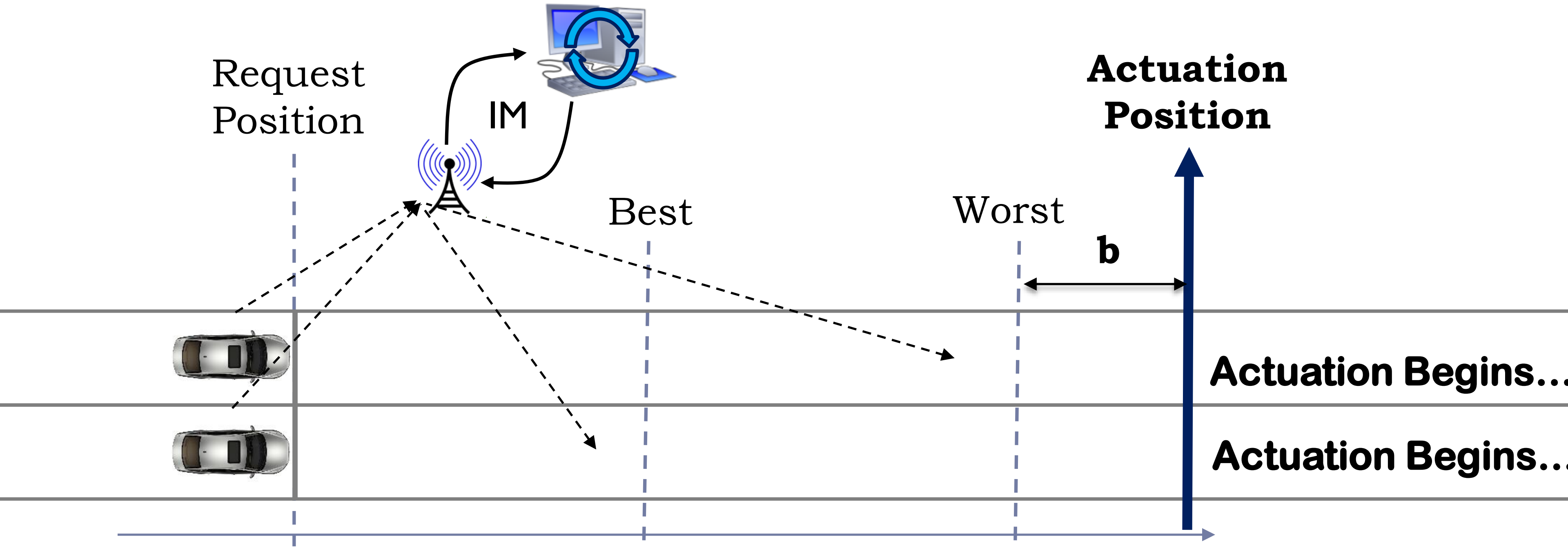
Ignoring RTD Will Cause Crashes



Crossroads Technique

- IM sets the execution location to be a fixed value as:

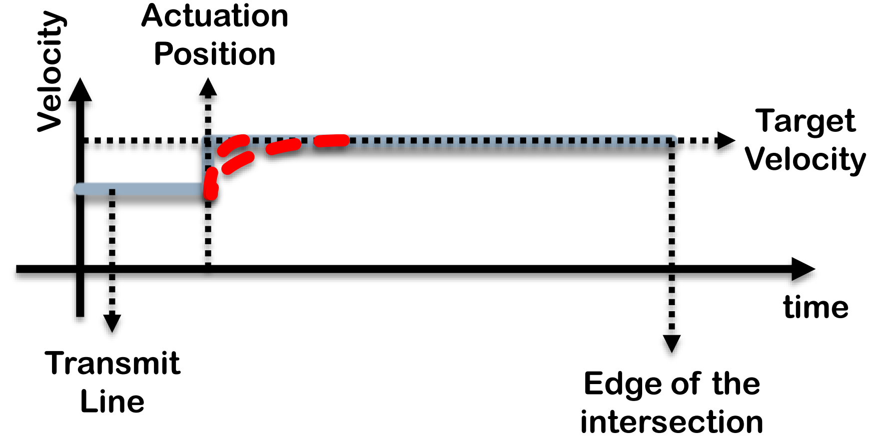
$$ActuationPosition = Request\ Position\ + (V_{max} \times WCRTD) + b$$

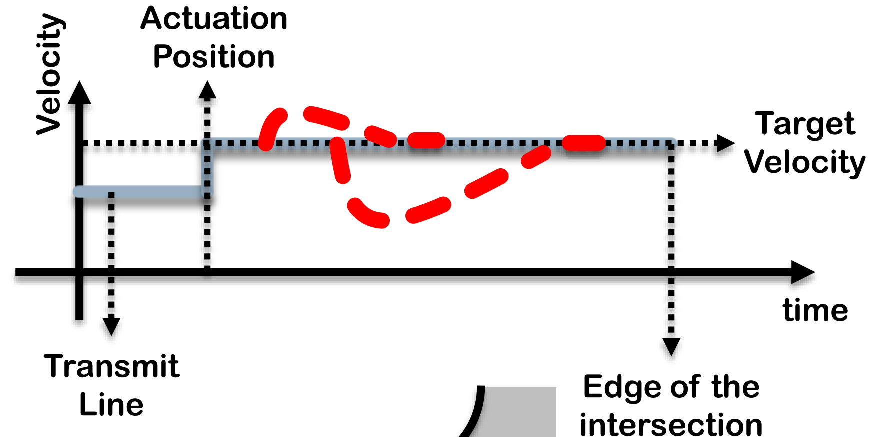


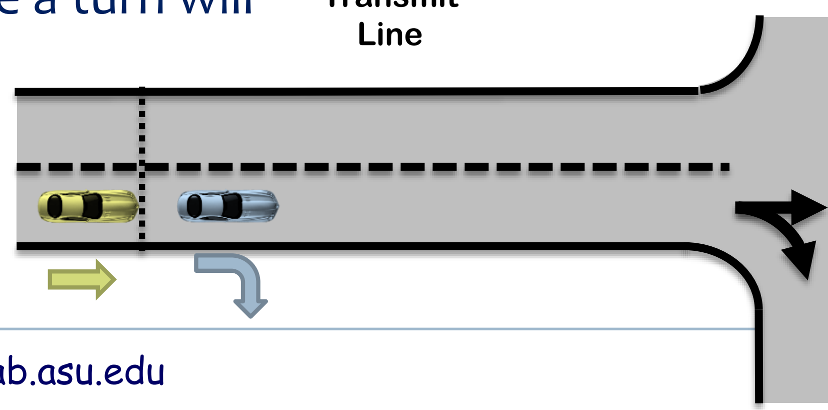
[1] Andert, Edward, Mohammad Khayatian, and Aviral Shrivastava. "Crossroads: Time-Sensitive Autonomous Intersection Management Technique." *Proceedings of the 54th Annual Design Automation Conference 2017*. ACM, 2017.

Issues of Crossroads

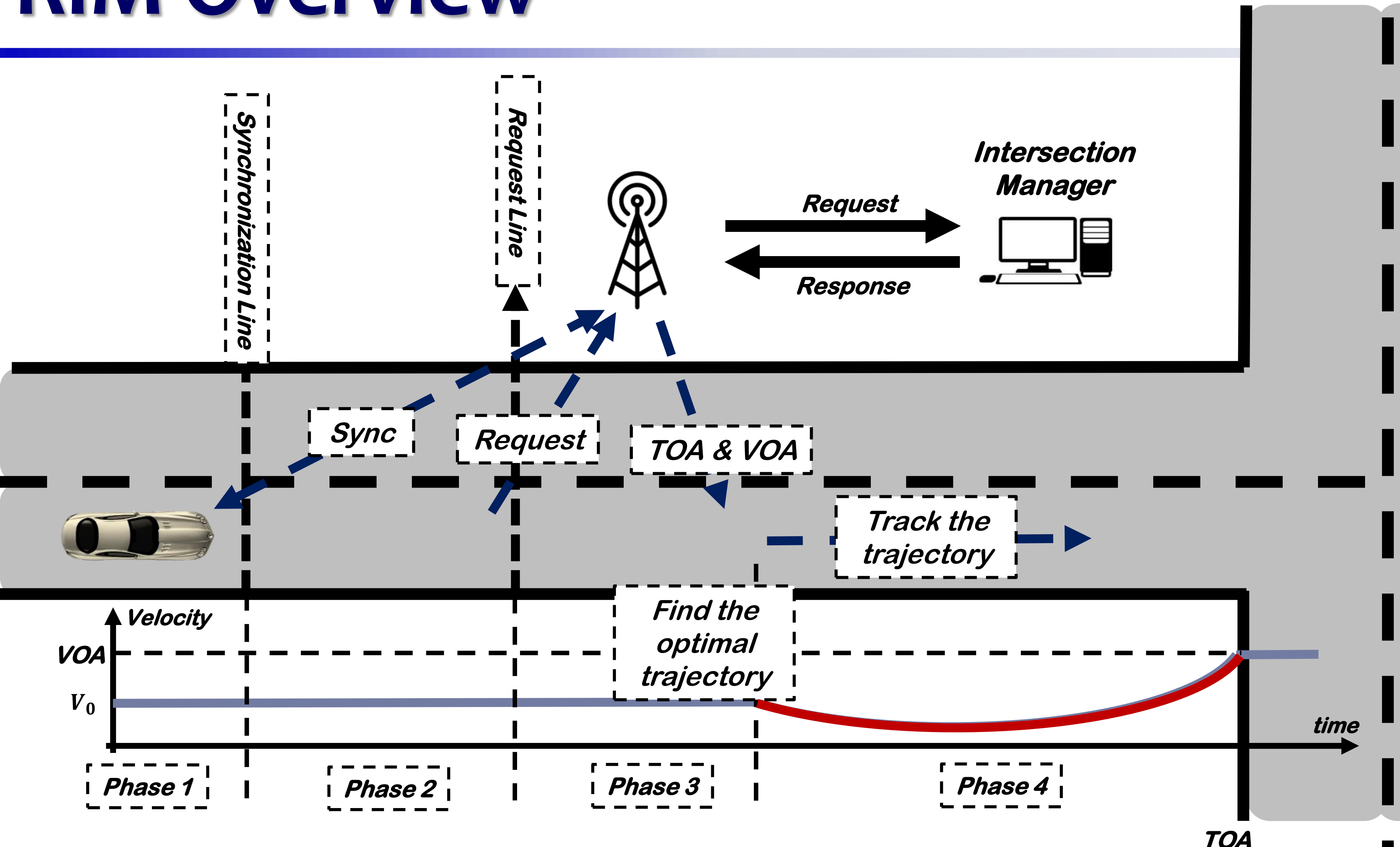
- Safety-related
  - 1) Vehicles are assumed to have zero actuation time
  - 2) Assigned velocity will be maintained until entering the intersection
  - What if a disturbance is applied to the vehicle?
    - Wind, bump, etc.
- Performance
- Vehicles that intend to make a turn will slow down others.







RIM Overview



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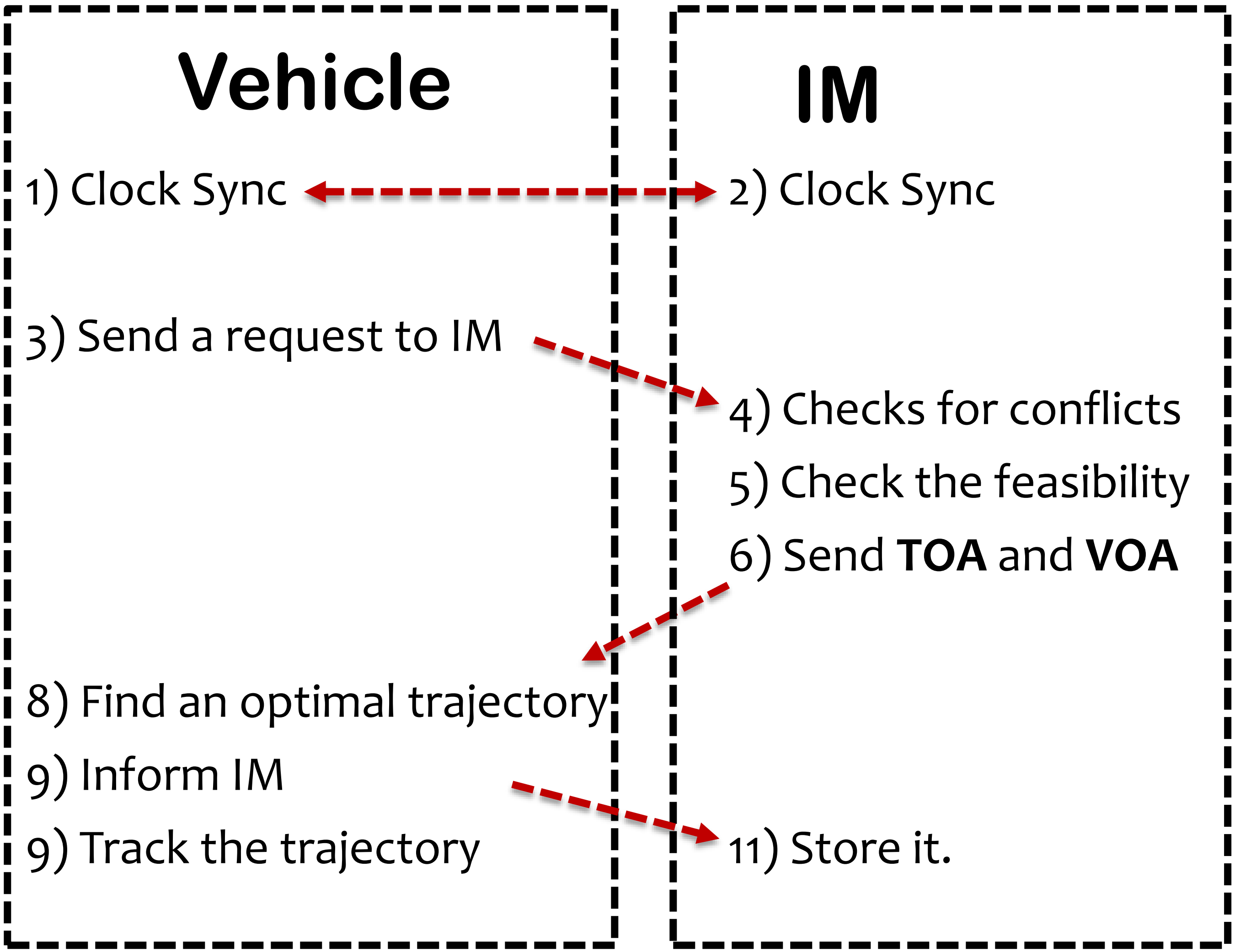
Our Approach: RIM



Algorithm 1: Vehicle Controller

```
if Sync line is crossed then
    result = synchronize();
    if result is not OK then
        if distance to transmit line is less than d_min then
            update(Trajectory, SD); /* slow down */
        end
        Goto Line 3;
    end
end
if Transmit line is crossed then
    V-Info = [P, V, a, TS, LO, a_max, a_min, ID];
    send(V-Info);
    Wait for the response;
    if response is timed out then
        if distance to intersection is less than d_min then
            update(Trajectory, SD); /* slow down */
        end
        Goto line 12;
    else
        [TOA, VOA] = getPacket(response) ;
        [A_0, B_0] = calculateTrajectory(TOA, VOA);
        update(Trajectory, [A_0, B_0]); /* set the Ref
         Trajectory */
    end
end
```

Algorithm 2: IM's Scheduling algorithm

```
Input: Request;
Outputs: [TOA, VOA];
while Request buffer is not empty do
    V-Info = read(buffer[first]);
    [TOA, VOA] = Schedule(V-Info, I-Info);
    Result = F-Check(TOA, VOA, V-Info, I-Info);
    if Result is OK then
        Send(TOA,VOA,Vehicle Info);
        update(I-Info)
    else
        Increase(TOA);
        Goto Line 6;
    end
end
```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Find the Optimal Trajectory

- We define a functional based on acceleration:

$$J = \int_{t_0}^{t_f} a^2 dt$$

- Solve using Fundamental Lemma of the Calculus Variation:

$$a(t) = A_0 t + B_0$$

- Linear acceleration is optimal!

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Find the Optimal Trajectory (cont.)

- Taking integral from acceleration we have:

$$v(t) = \frac{1}{2}A_0 t^2 + B_0 t + v_0$$

- Taking integral from velocity we have:

$$\boldsymbol{x(t) = \frac{1}{6}A_0 t^3 + \frac{1}{2}B_0 t^2 + v_0 t + x_0}$$

- Substituting the initial and final conditions ($x(t_0) = x_0, x(t_f) = x_f, v(0) = v_0, v(t_f) = v_f$, we have:

$$v(t_f) = \frac{1}{2}A_0 t_f^2 + B_0 t_f + v_0$$

$$x(t_f) = \frac{1}{6}A_0 t_f^3 + \frac{1}{2}B_0 t_f^2 + v_0 t_f + x_0$$

$$A_0 = \frac{6(2x_0 - 2x_f + t_f v_0 + t_f v_f)}{t_f^3}$$

$$B_0 = \frac{-2(3x_0 - 3x_f + 2t_f v_0 + t_f v_f)}{t_f^2}$$

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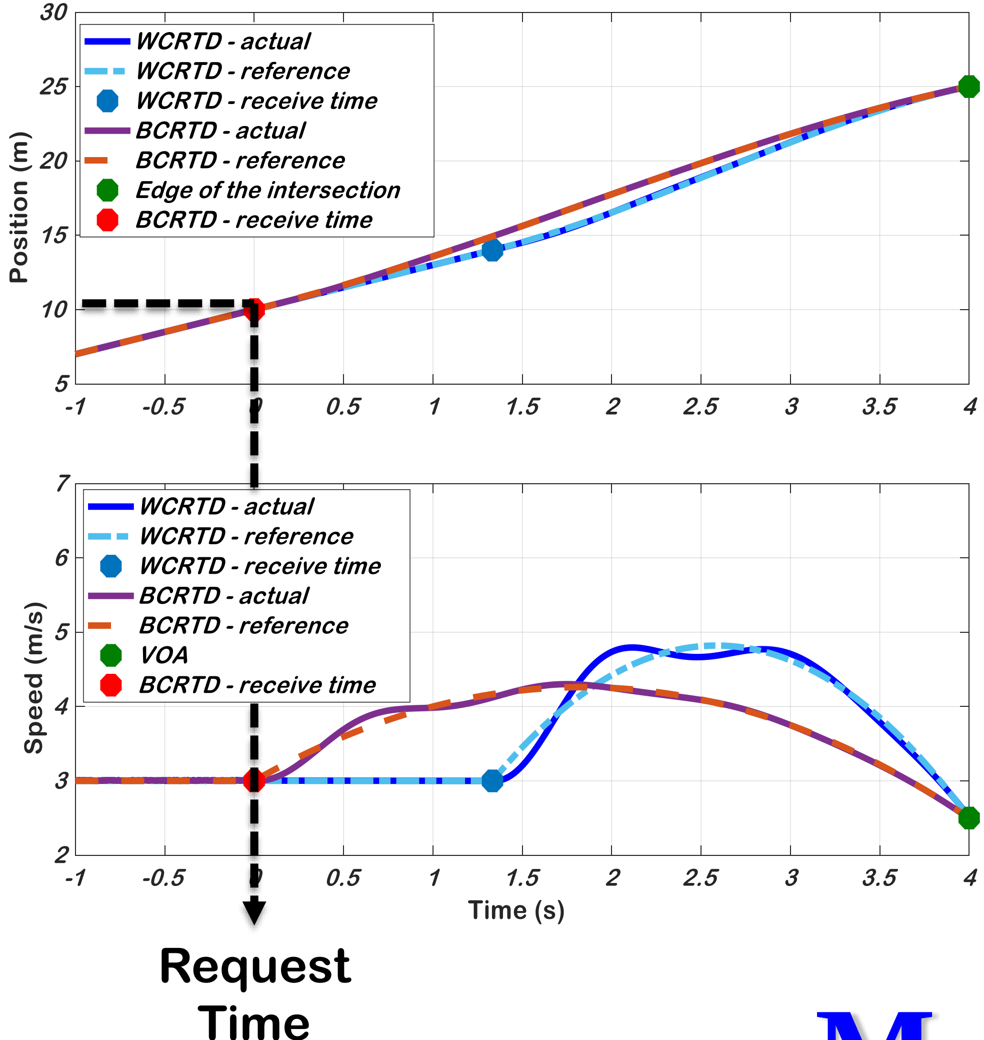
Dealing with the Round-trip Delay

- As soon as TOA and VOA are received, the optimal trajectory is determined.
- All determined trajectories will meet the TOA and VOA requirement.
- Vehicles will control the position instead of velocity



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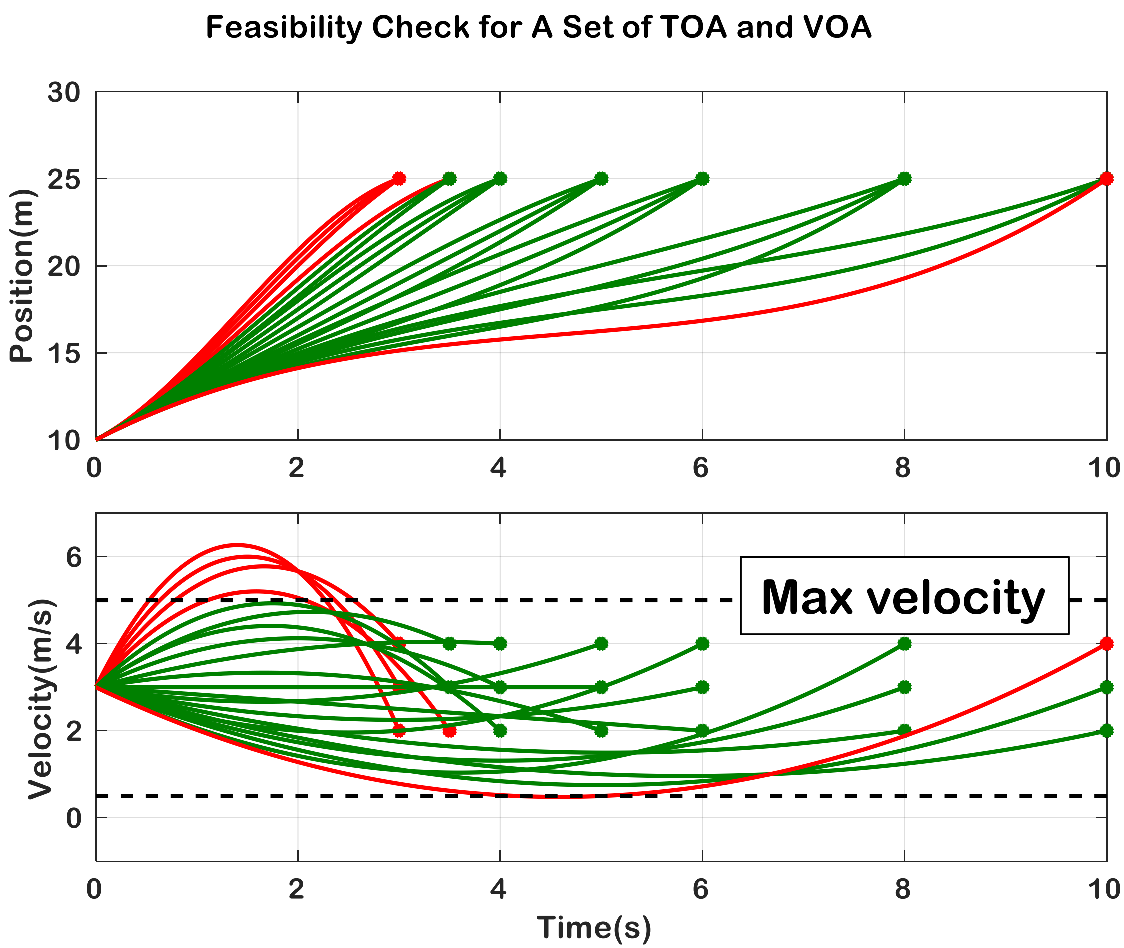
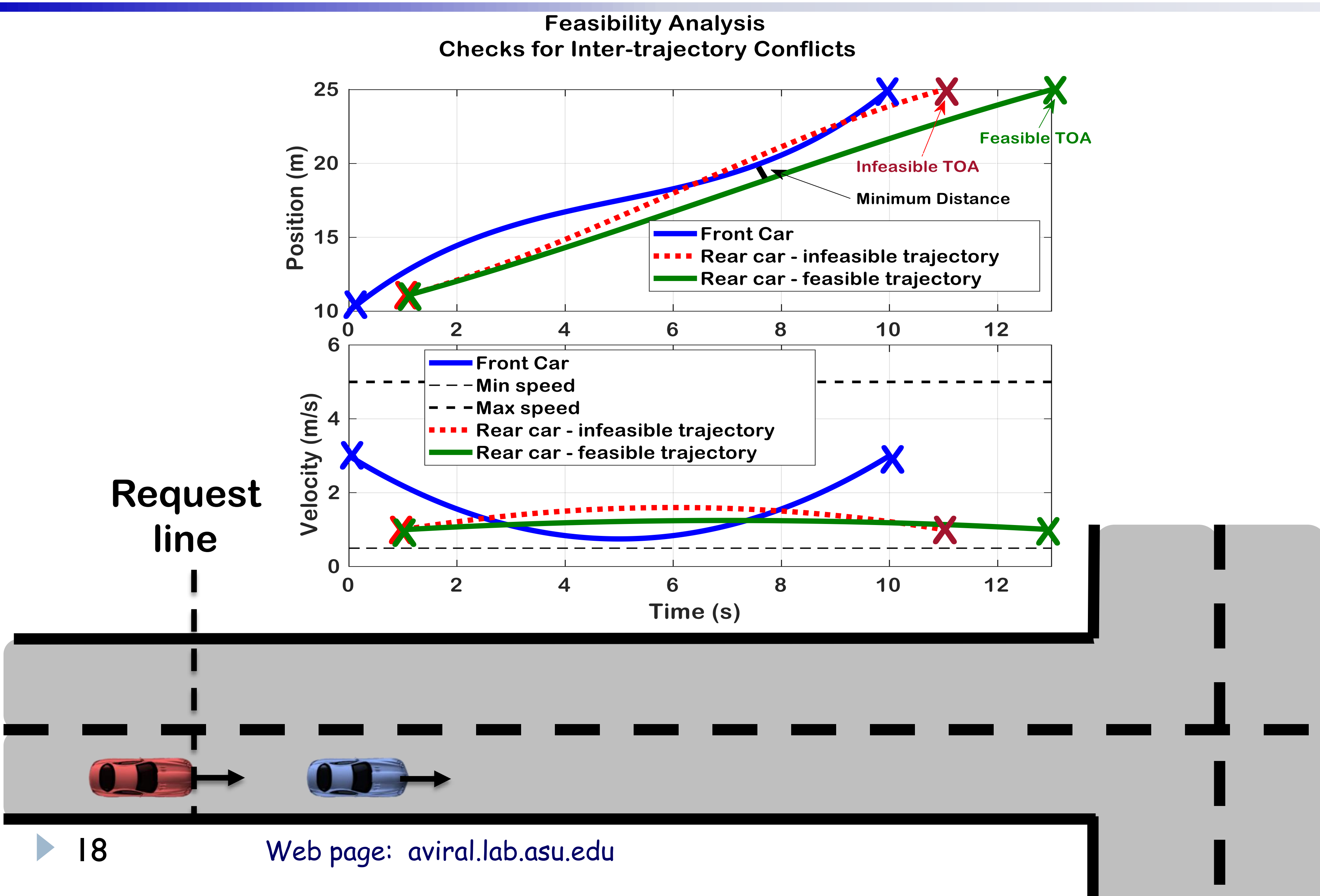
Feasibility of VOA and TOA

- Is the assigned TOA and VOA feasible?
- Check for min and max acceleration rates
  - Vehicles have limited acc/dec power
- Check for min and max velocities
  - Road speed limit



Feasibility of VOA and TOA



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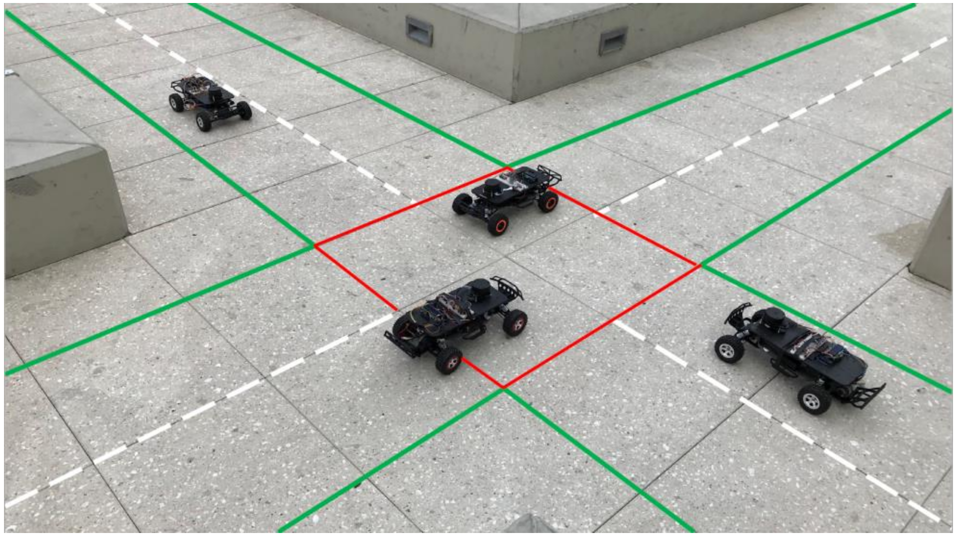
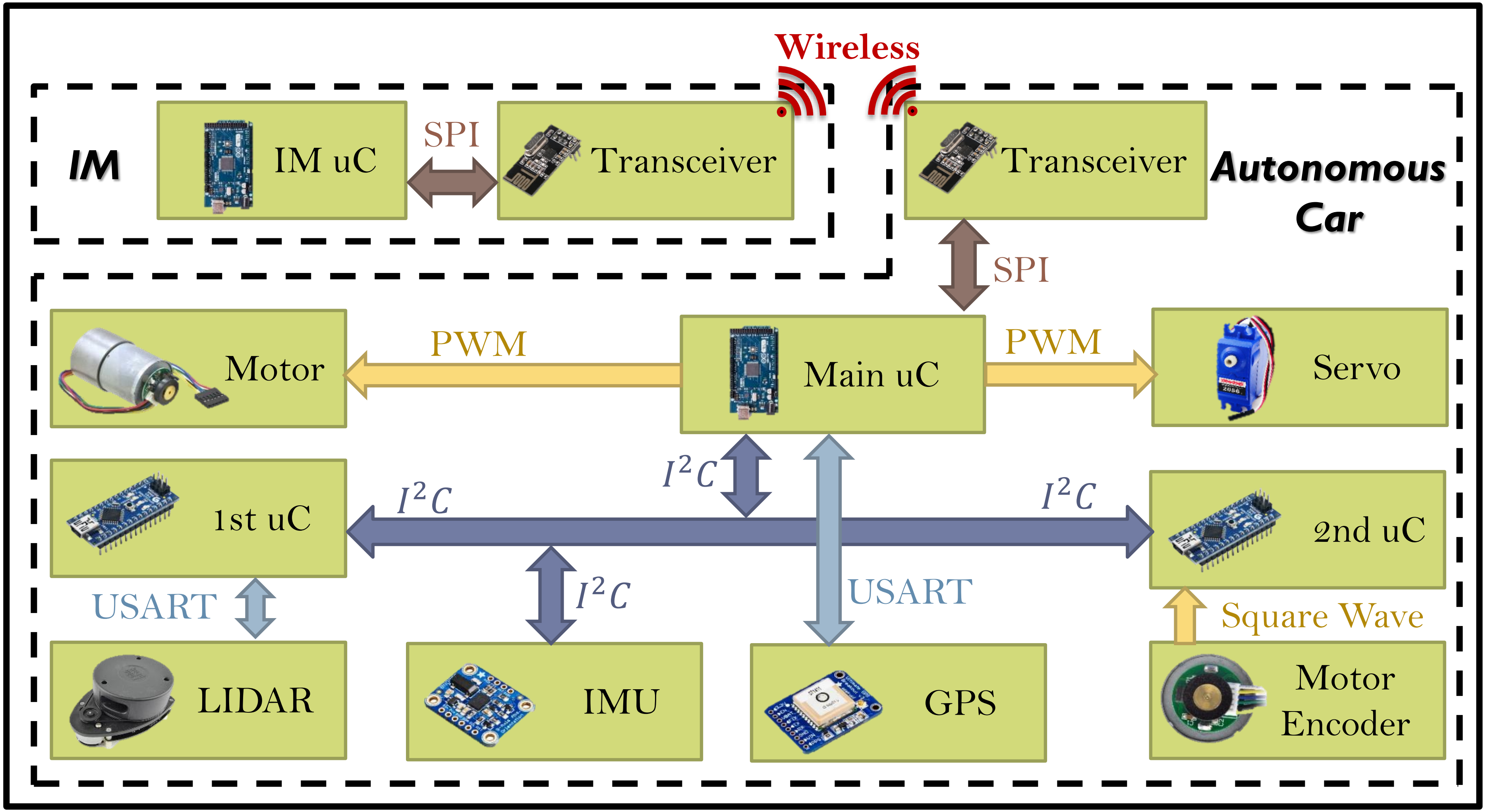
Our Testbed

- 4-way intersection
- 1/10 scale RC cars on Traxxas chassis
- Vehicle size = 30 cm x 57 cm
  max speed = 5 m/s (11.1 mph)
- Lane width = 60 cm
- Transmit line distance = 3 m

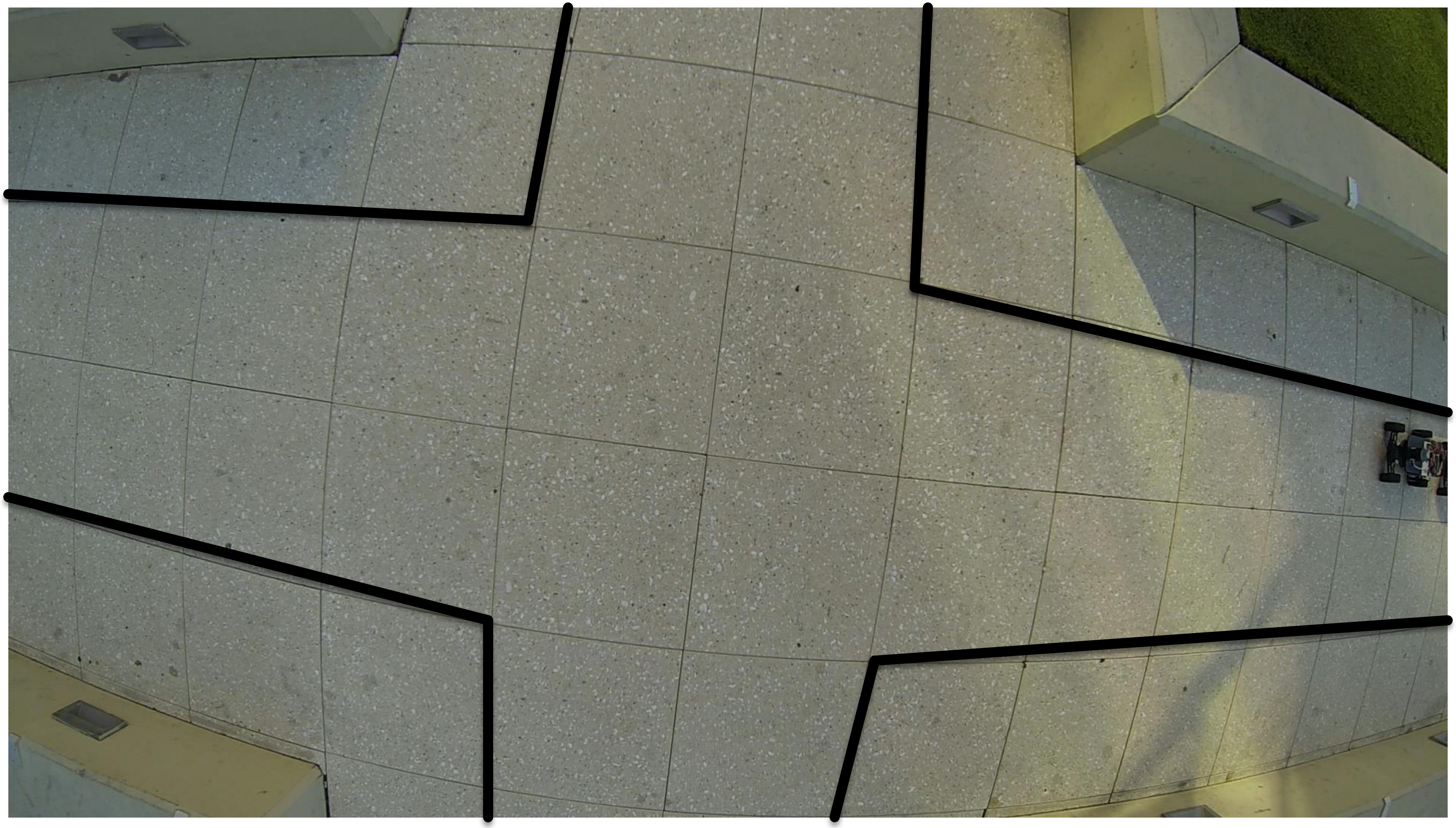


- NTP protocol for clock synchronization (10 ms accuracy)
- PID controller for position trajectory tracking
- 3 types of communication packets
  - Sync (7 Bytes), Request (30 Bytes), Receive (30 Bytes)

IM & Car Schematic

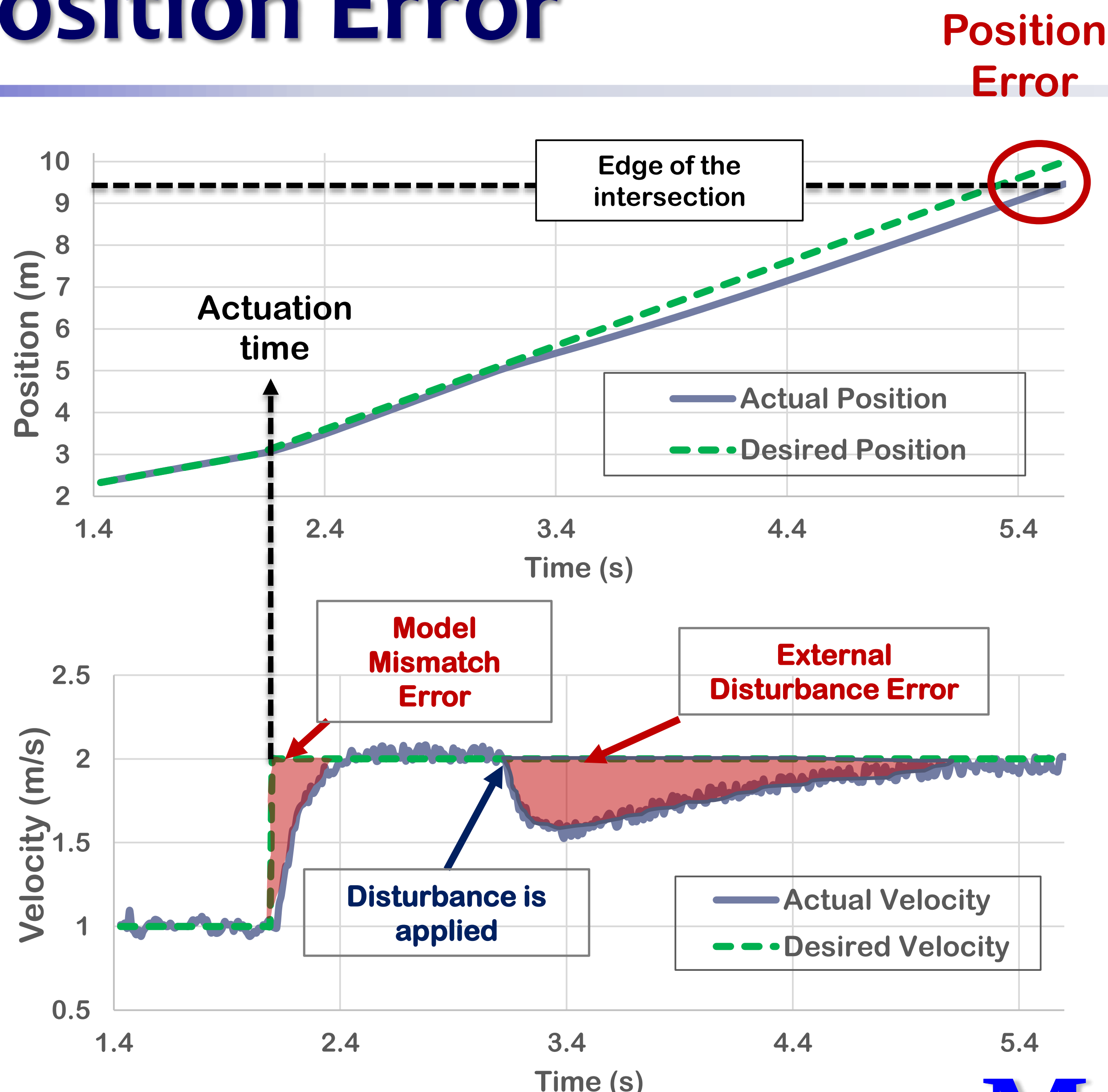


Video of our Intersection



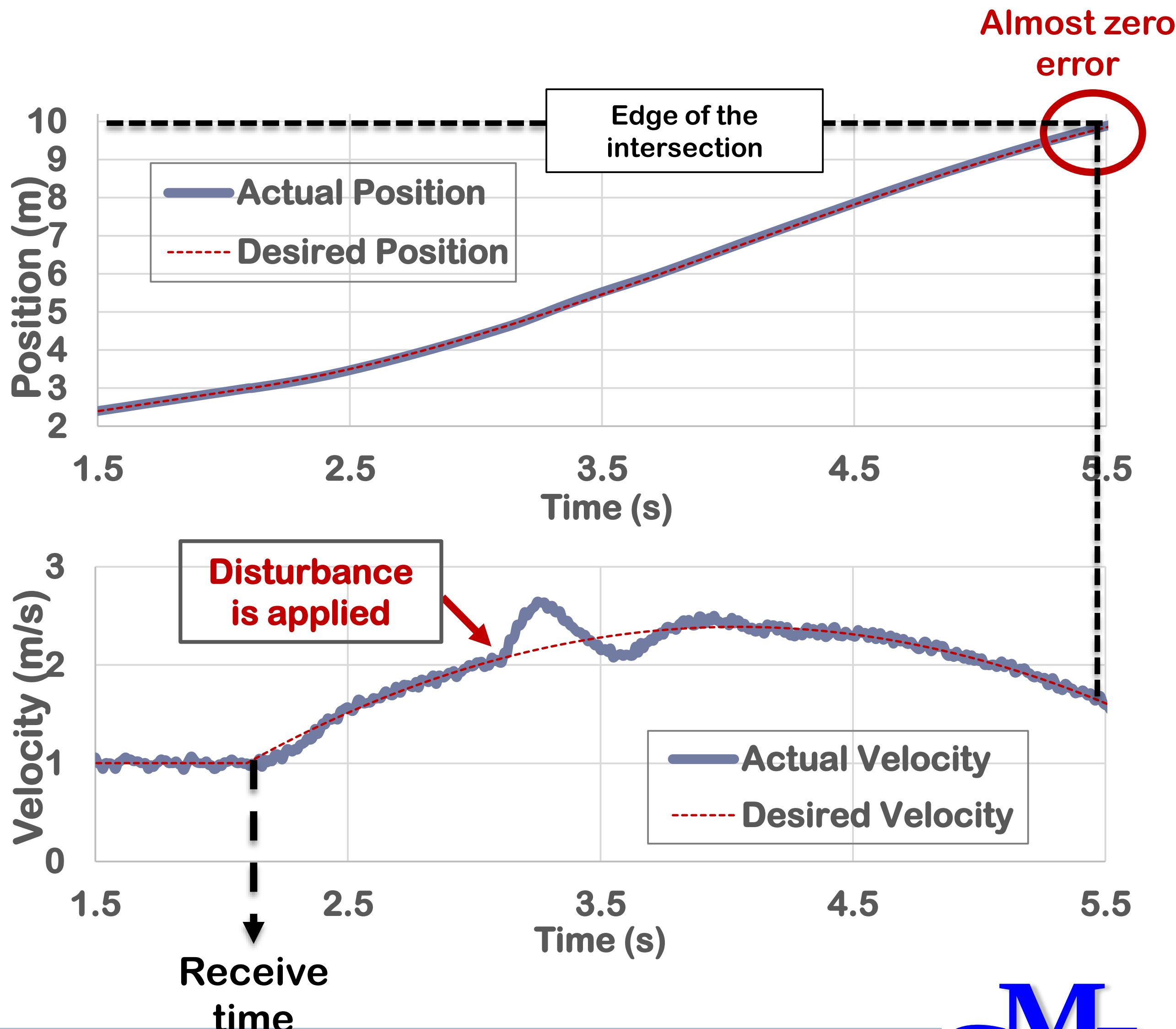
Crossroad Position Error

- 10 % model mismatch is added.
- An external disturbance of 5% is applied
- Monitor position and velocity of a CAV.



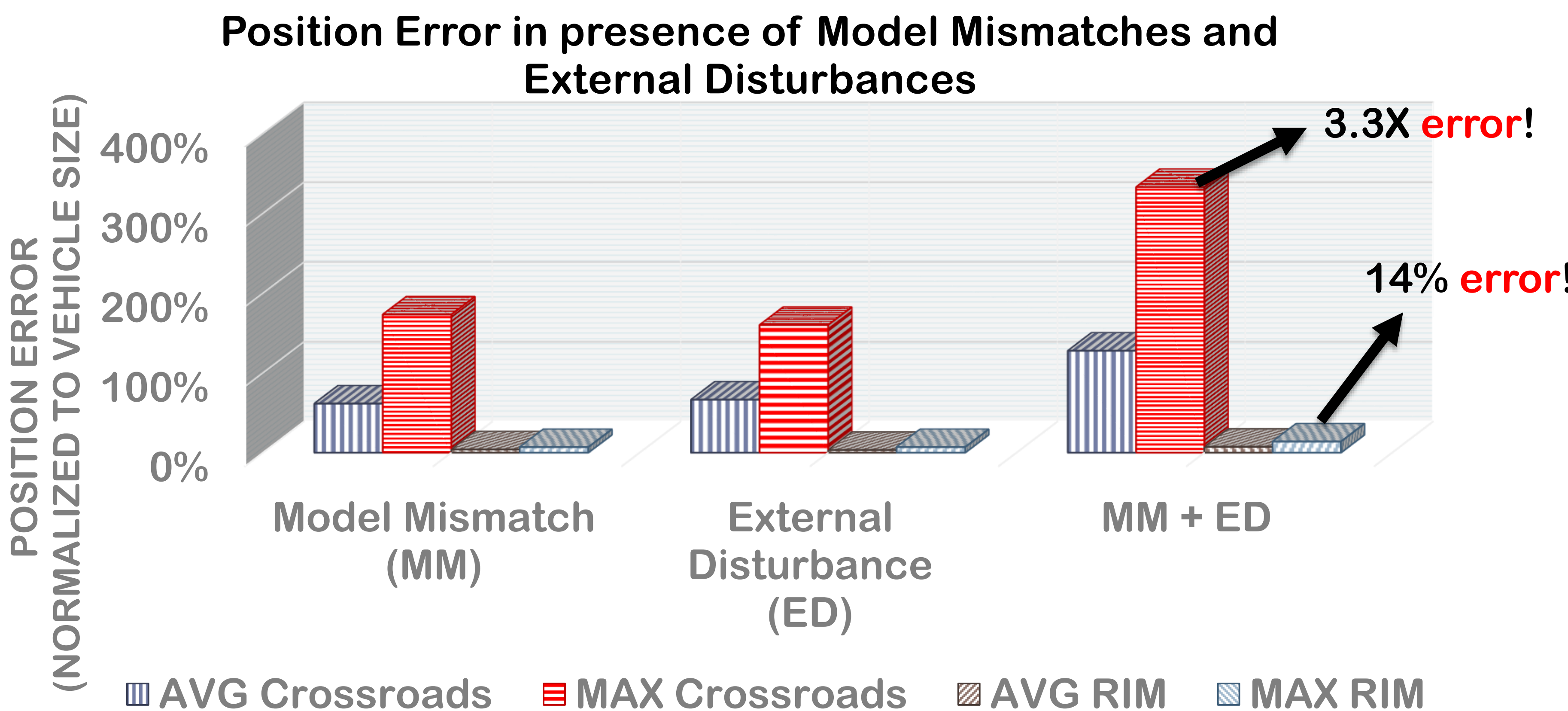
RIM is Robust

- 10 % model mismatch is added.
- An external disturbance of 5% is applied
- Monitor position and velocity of a CAV.



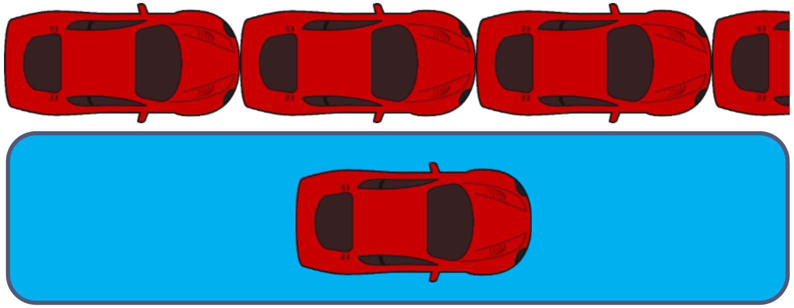
Robustness of RIM vs Crossroads

- We repeated our experiment 50 times, for different VOAs and TOAs.



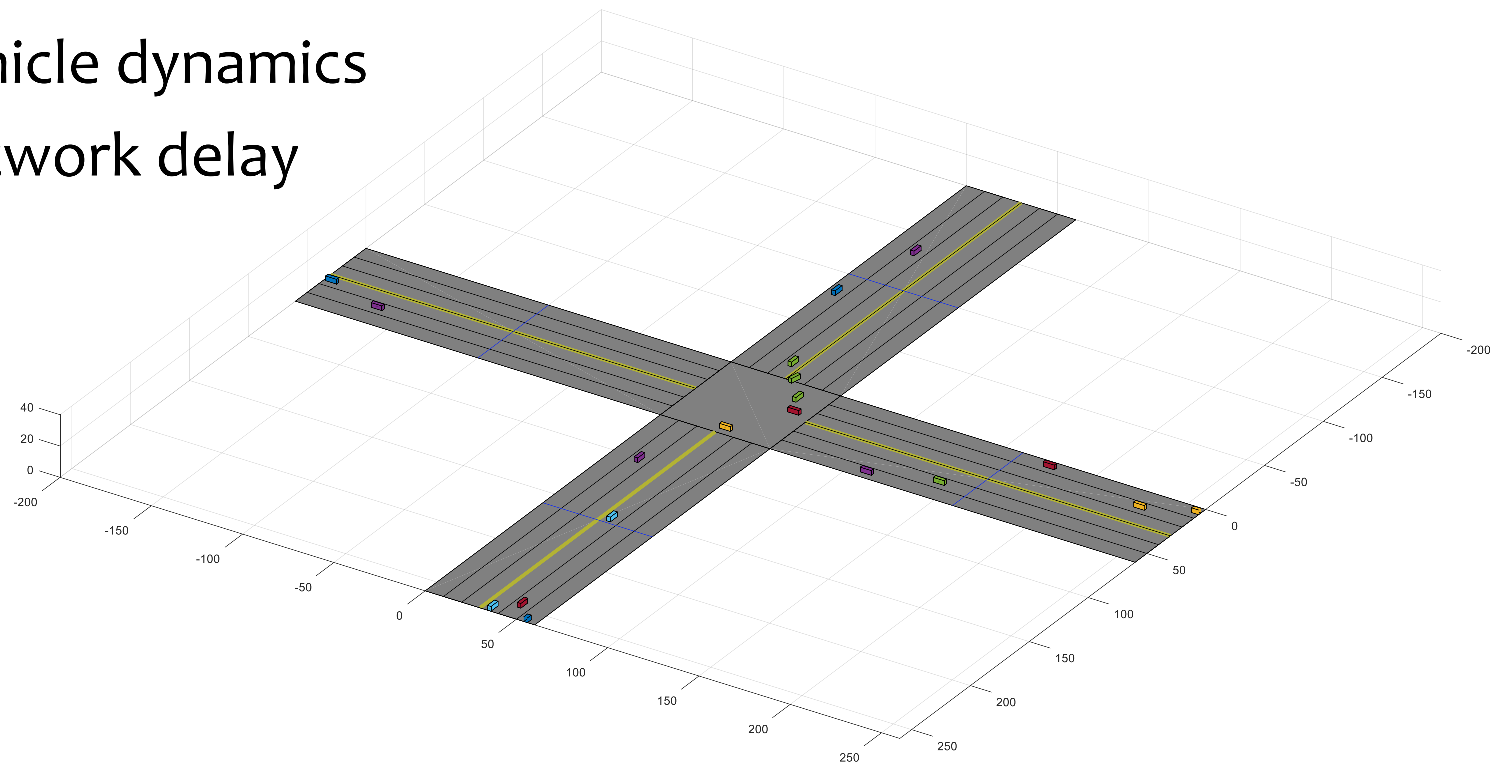
Crossroads needs a Safety Buffer

- Since Crossroads does not consider model mismatches and external disturbances, it's not safe!
- However, Crossroads can still work if we consider a safety buffer of 3.3X of size of the car.



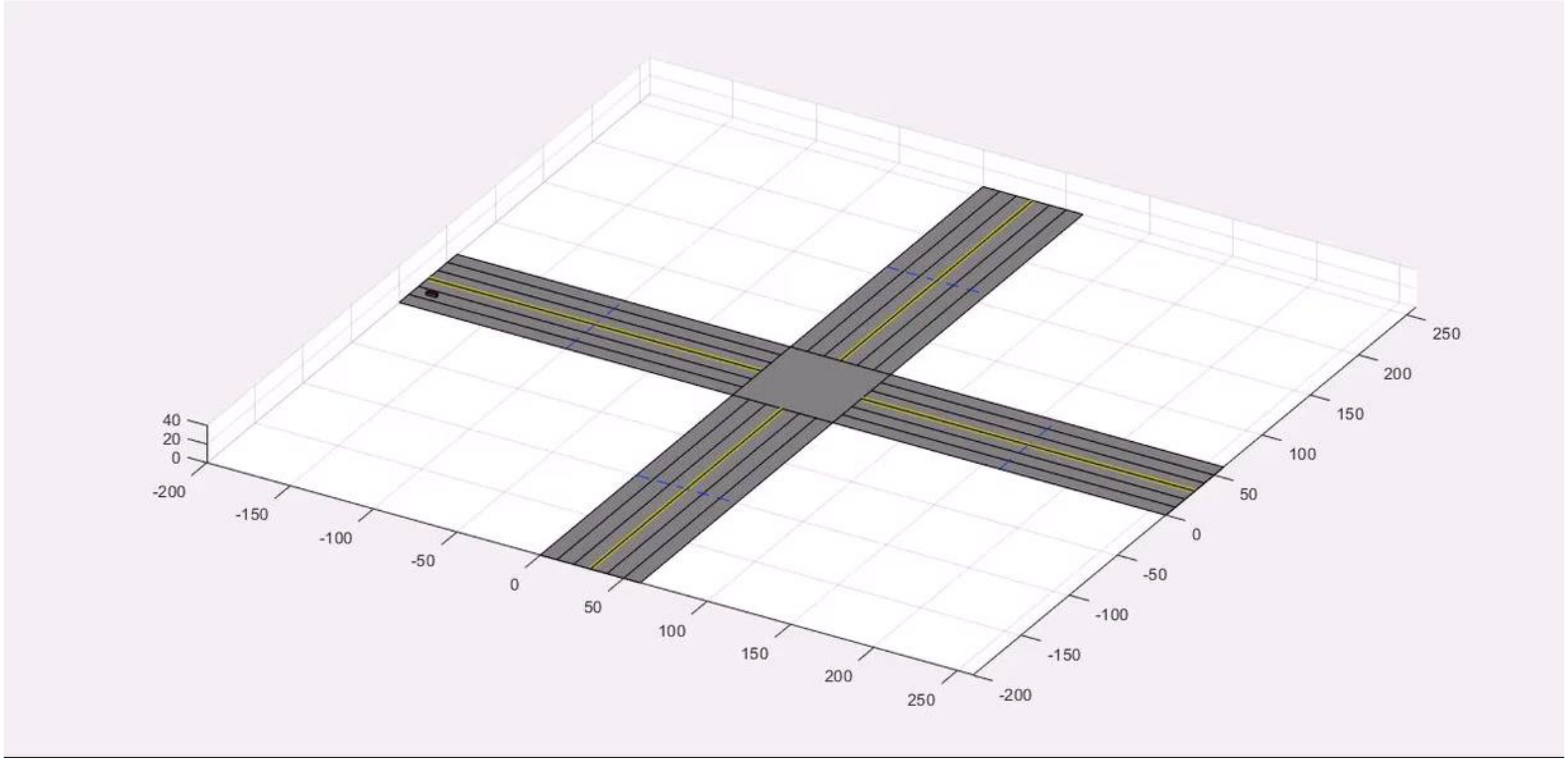
Evaluation using our Simulator

- Developed in MATLAB® [1]
- Scale to multi-lane intersection
- Variable traffic flow rates
- Model vehicle dynamics
- Model network delay



[1] Available Online: https://github.com/mkhayatian/Traffic-Intersection-Simulator-for-Autonomous-Vehicles

Simulator Video



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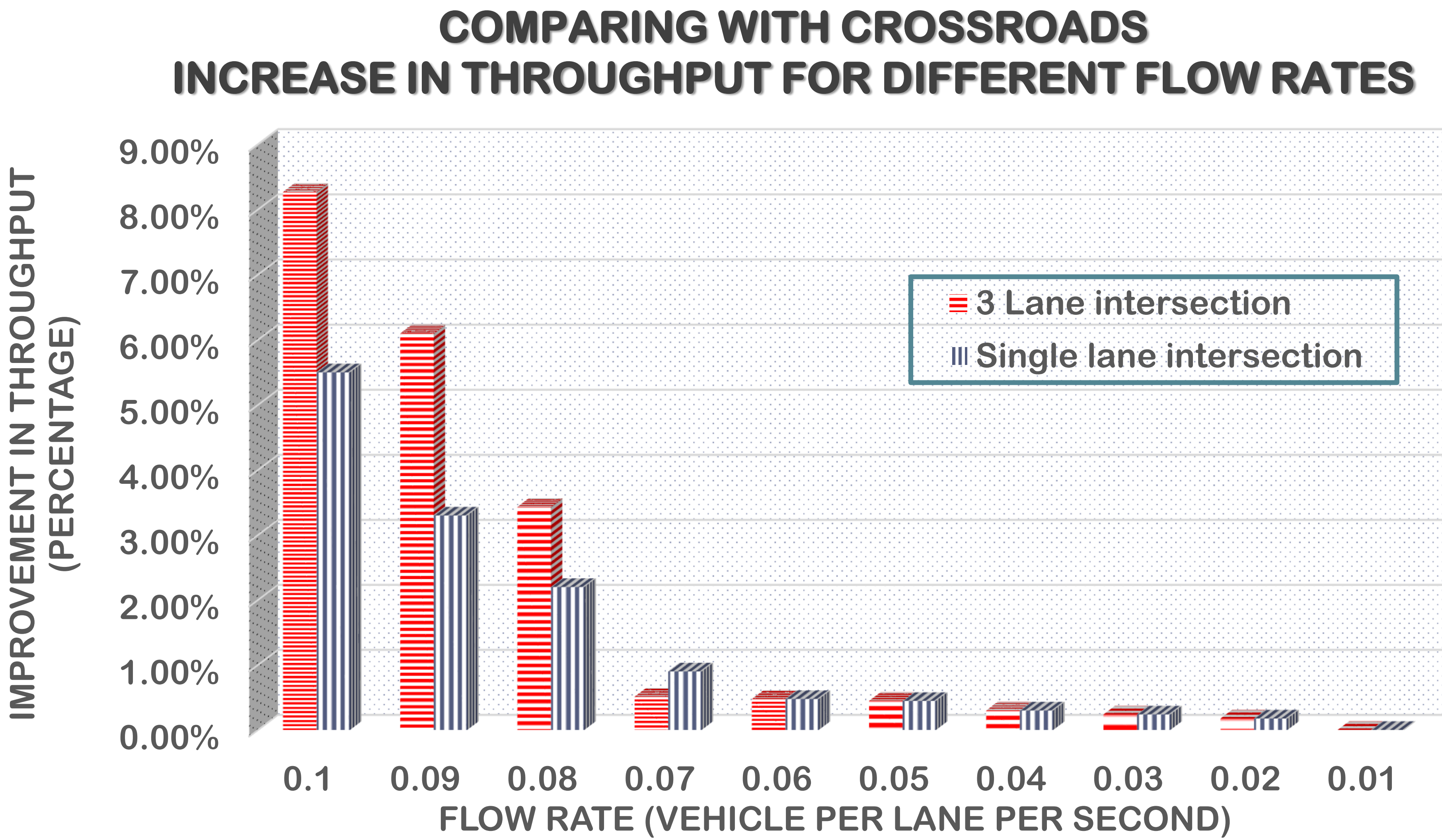
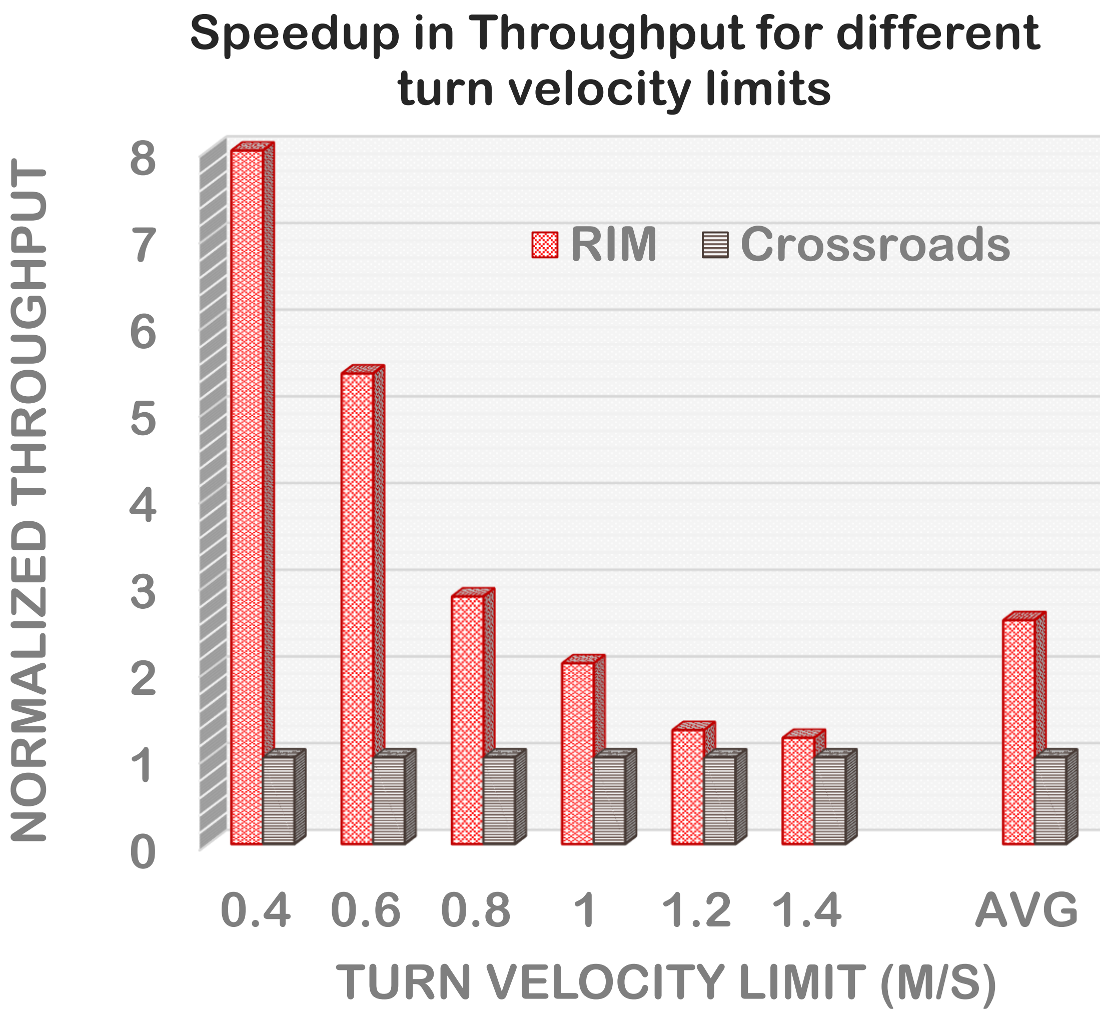
Throughput Improvement



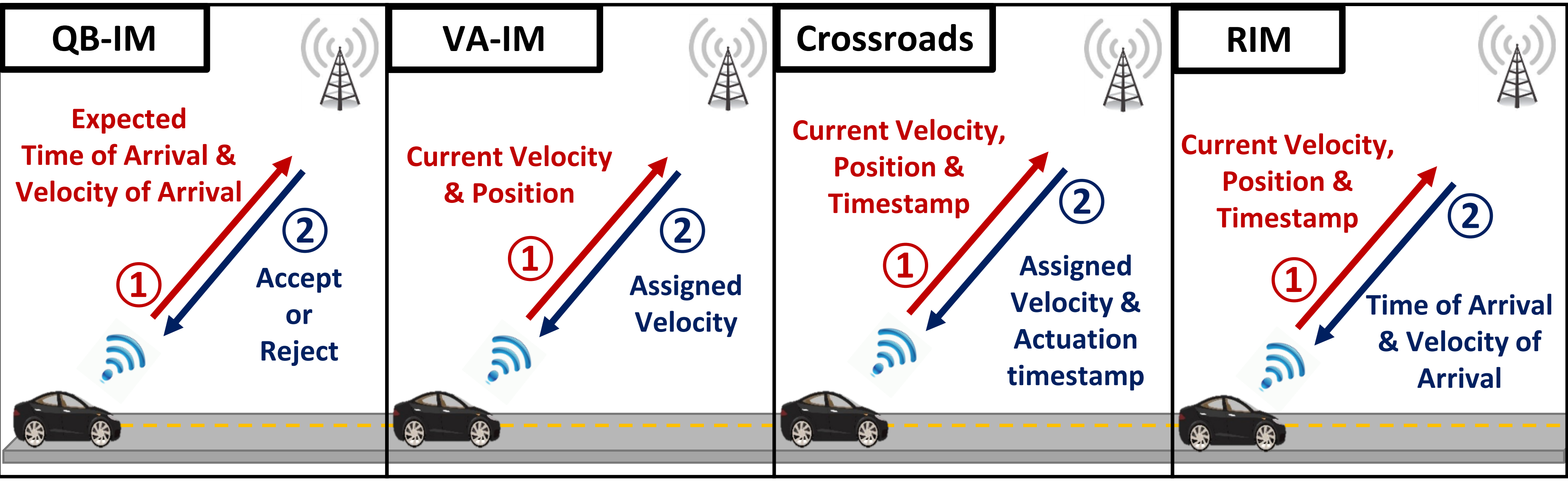
Efficiently Making a Turn

- Crossroads & VA-IM
  - A ***constant*** Velocity is assigned.
  - To avoid rollover, turn speed is low.
  - Vehicles that intend to make a turn will slow down behind vehicles.
- RIM
  - Vehicles can adjust their speed.



Position of Our Work

- Query-based (AIM)
- Velocity Assignment
- Crossroads
- RIM



Conclusion

- We explored safety concerns of previous intersection management techniques.
  - Network delay
  - Vehicle dynamics

- We presented a ***robust*** intersection management interface for connected autonomous vehicles.
  - Model mismatch
  - External disturbances
  - Efficient

Question?